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Potentials for energy efficiency improvement in the US cement industry

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Abstract

This paper reports on an in-depth analysis of the US cement industry, identifying cost-effective energy efficiency measures and potentials. Between 1970 and 1997, primary physical energy intensity for cement production (SIC 324) dropped 30%, from 7.9 GJ/t to 5.6 GJ/t, while specific carbon dioxide emissions due to fuel consumption and clinker calcination dropped 17%, from 0.29 tC/tonne to 0.24 tC/tonne. We examined 30 energy-efficient technologies and measures and estimated energy savings, carbon dioxide savings, investment costs, and operation and maintenance costs for each of the measures. We constructed an energy conservation supply curve for the US cement industry which found a total cost-effective energy saving of 11% of 1994 energy use for cement making and a saving of 5% of total 1994 carbon dioxide emissions. Assuming the increased production of blended cement, the technical potential for energy efficiency improvement would not change considerably. However, the cost-effective potential would increase to 18% of total energy use, and carbon dioxide emissions would be reduced by 16%. This demonstrates that the use of blended cements is a key cost-effective strategy for energy efficiency improvement and carbon dioxide emission reductions in the US cement industry. Published by Elsevier Science Ltd.

1. Introduction

In 1994 the manufacturing sector consumed 23 EJ of primary energy in the United States, almost one quarter of all energy consumed that year [1]. Within manufacturing, a subset of raw materials transformation industries (cement, primary metals, pulp and paper, chemicals, petroleum refining) require significantly more energy to produce than other manufactured products.

This report reflects an in-depth analysis of one of these energy-intensive industries — cement,

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the binding agent in concrete and mortar — identifying energy savings and carbon dioxide emissions reduction potentials. We analyze the cement industry at the aggregate level (Standard Industrial Classification 324), which includes establishments engaged in manufacturing hydraulic cements, including portland, natural, masonry, and pozzolana cements.

The production of cement is an energy-intensive process that results in the emission of carbon dioxide from both the consumption of fuels (primarily for the kiln) and from the calcination of limestone.

In this article we will begin with a discussion of the methodology used to assess the potential for energy efficiency improvement as well as the cost-effectiveness. This is followed by a description of the cement making processes and historic trends in energy use and carbon dioxide emissions in the US cement industry for the period from 1970 until 1997. We then assess the baseline of the energy intensity of the cement making processes. This is the basis for the following analysis of energy efficient practices and technologies, as well as the analysis of the cost-effective potential for energy efficiency improvement potential.

2. Methodology

The analysis consists of three steps. First, after an analysis of historic trends, we establish a 1994 baseline for energy and material use, using data from the last year for which detailed national energy statistics are available [1,2]. The second step is the analysis and characterization of energy-efficient technologies to improve energy efficiency, and determination of the potential application and impact of these measures. Finally, we assess the cost-effectiveness of the potential for energy efficiency improvement, using a so-called energy conservation supply curve.

Throughout this paper, primary energy is calculated using a conversion rate from final to primary electricity of 3.08 (equivalent to a power generation efficiency of 32.5%), including transmission and distribution losses. Energy is expressed in higher heating value (HHV), as is common in US energy statistics. Carbon dioxide emissions are expressed in metric tons carbon. The carbon conversion factors used for calculating carbon emissions from energy consumption are taken from the Energy Information Administration [3] and IPCC [4]. In the historic trend analysis, electricity conversion factors vary annually based on the fuel mix used for power generation. Production is expressed in metric tons.

2.1. Establishing a baseline for energy use in the US cement industry

Energy use for each of the processes has been subdivided to the major processes used in the cement industry. The main energy-using processes are raw material preparation, clinker making and finish grinding (or cement making). Energy consumption data (see Table 1) are based on data from the Portland Cement Association [5], United States Geological Survey [2] and Manufacturing Energy Consumption Survey [1]. When data on specific sub-processes were not available, consumption estimates were based on process energy intensity estimates from available literature. CO_2 emissions from calcination are included in the emissions estimate.

2.2. Characterization of energy efficient technologies

To analyze the potential for reducing energy use and carbon dioxide emissions from cement production in the US, we compiled information on the costs, energy savings, and carbon dioxide emissions reductions of a number of technologies and measures. The technologies and measures fall into two categories: commercially available measures that are currently in use in cement plants worldwide and advanced measures that are either only in limited use or are near commercialization. We focus on retrofit measures using commercially available technologies, but many of these technologies are applicable for new plants as well. For each technology or measure, we estimate costs and energy savings per tonne of cement produced in 1994. We then calculate carbon dioxide emissions reductions based on the fuels used at the process step to which the technology or measure is applied. Fuel and electricity savings for each efficiency measure were usually calculated as savings per tonne product. To convert savings from a per tonne product basis to a per tonne cement basis we multiplied the savings by the ratio of throughput (production from a specific process) to total cement. Operating and capital costs are also calculated on a cement basis according to the same methodology as fuel and electricity savings. Our determination of the share of production to which each measure is applied was based on a variety of information sources on the US cement industry in 1994 and expert judgment.

Finally, carbon dioxide emissions reductions for each measure were calculated based on a weighted average carbon dioxide emissions coefficient (tC/GJ) for each process step. We have attempted to account for interactive effects when estimating the potential savings through assessing the possible degree of implementation, as well as interactive effects caused by the order of implementation of technologies. We generally assumed that the most cost-effective technology was implemented first, unless technical reasons determine the order of implementation.

2.3. Energy conservation supply curves

Supply curves are a common tool in economics. In the 1970s, energy conservation supply curves were developed by energy analysts as a means of ranking energy conservation investments alongside investments in energy supply in order to assess the least cost approach to meeting energy service needs. Conservation supply curves rank energy efficiency measures by their “cost of conserved energy” (CCE), which accounts for both the costs associated with implementing and maintaining a particular technology or measure and the energy savings associated with that option over its lifetime. The CCE of a particular option is calculated following Eq. (1).

$$\mathrm{CCE} = \frac{\text{Annualized Investment+Annual Change in O\&M Costs}}{\text{Annual Energy Savings}} \tag{1}$$

The annualized investment is calculated following Eq. (2).

$$\text{Annualized Investment} = \text{Capital Cost} \times \frac{d}{(1-(1+d)^{-n})} \tag{2}$$

where d is the discount rate and n is the lifetime of the conservation measure. CCEs are calculated for each measure that can be applied in a certain sector or subsector and then ranked in order of increasing CCE. Once all options have been properly ranked, a conservation supply curve can be constructed. Defining “cost-effective” involves choosing a discount rate that reflects the desired perspective (e.g. customer, society). Then all measures that fall below a certain energy price, such as the average price of energy for the sector, can be defined as cost-effective.

The CCEs are plotted in ascending order to create a conservation supply curve. This curve is a snapshot of the total annualized cost of investment for all of the efficiency measures being considered at that point in time. The width of each option or measure (plotted on the *x*-axis) represents the annual energy saved by that option. The height (plotted on the *y*-axis) shows the option’s CCE.

The advantage of using a conservation supply curve is that it provides a clear, easy-to-understand framework for summarizing complex information about energy efficiency technologies, their costs, and the potential for energy savings. The curve can avoid double counting of energy savings by accounting for interactions between measures, is independent of prices, and also provides a framework to compare the costs of efficiency with the costs of energy supply technologies.

This conservation supply curve approach also has certain limitations. In particular, the potential energy savings for a particular sector are dependent on the measures that are listed and/or analyzed at a particular point in time. There may be additional energy efficiency measures or technologies that do not get included in an analysis, so savings may be underestimated. The costs of efficiency improvements (initial investment costs plus operation and maintenance costs) do not include all the transaction costs for acquiring all the appropriate information needed to evaluate and choose an investment and there may be additional investment barriers as well that are not accounted for in the analysis.

Many analysts use internal rate of return (IRR) to rate the cost effectiveness of various investments, which is the value of the discount rate to make the net benefits stream equal to the initial investment. A key difference between CCE and IRR is that with an IRR the fuel price for the analysis period is included in the calculation (since energy savings are quantified on a dollar basis), and therefore has a direct effect on the evaluation of a measure. With the CCE calculation changes in fuel prices will not change the CCE of a measure but will change the number of measures that are considered cost effective.

For our analysis, we used a 30% real discount rate, reflecting the cement industry’s hurdle rate. We use an industry average weighted fuel cost in our calculation based on energy data provided by the Portland Cement Association, US Geological Survey, and cost data from EIA [1]. We include a weighted fuel cost and we use the source price of electricity.

In the process of developing the supply curves we also noted that several efficiency measures provide other environmental benefits in addition to energy savings. For example, production of blended cement will reduce the landfilling of waste materials like fly-ash, and will lengthen the life-time of limestone reserves. More efficient pre-calciner kilns will not only reduce energy use but also NO_x, and SO_x emissions from the kiln. While we believe that including quantified estimates of other benefits would increase the number of cost-effective efficiency options, we have not included such estimates in this current work. This is a subject, however, that merits continued research.

3. Description of cement making process

The US cement industry is made up of clinker plants, which produce clinker, cement plants that grind clinker obtained elsewhere, or a combination of the two, an integrated plant. Clinker is produced through a controlled high-temperature burn in a kiln of a measured blend of calcareous rocks (usually limestone) and lesser quantities of siliceous, aluminous, and ferrous materials. The kiln feed blend (also called raw meal or raw mix) is adjusted depending on the chemical composition of the raw materials and the type of cement desired. Cement plants grind clinker and add a variety of additives to produce cement, while integrated plants both manufacture clinker and grind it to make cement. The production process consists of three main steps: raw material mining and preparation, clinker production, and finish grinding.

3.1. Raw material mining and preparation

The most common raw materials used for cement production are limestone, chalk and clay [6]. Most commonly the main raw material, the limestone or chalk, is extracted from a quarry very close to the plant. The collected raw materials are selected, crushed, ground, so that the resulting mixture has the desired fineness and chemical composition for delivery to the pyro-processing systems.

Raw material preparation is an electricity-intensive production step. The raw materials are further processed and ground. The grinding differs with the pyro-processing process used. The raw materials are prepared for clinker production into a “raw meal” either by dry or wet processing. In dry processing, the materials are ground into a flowable powder in ball mills or in roller mills. In a ball (or tube) mill, steel balls are responsible for decreasing the size of the raw material pieces in a rotating tube. Rollers on a round table fulfil this task of comminution in a roller mill. The raw materials may be further dried from waste heat from the kiln exhaust before pyro-processing. The moisture content in the (dried) feed of the dry kiln is typically around 0.5% (0–0.7%). When raw materials contain more than 20% water, wet processing can be preferable.[1] In the wet process raw materials are ground with the addition of water in a ball mill to produce a slurry typically containing 36% water (range of 24–48%). Various degrees of wet processing exist, e.g. semi-wet (moisture content of 17–22%) to reduce the fuel consumption in the kiln.

3.2. Clinker production (pyro-processing)

Clinker production is the most energy-intensive stage in cement production, accounting for over 90% of total industry energy use. Clinker is produced by pyro-processing in large kilns. These kiln systems evaporate the free water in the meal, calcine the carbonate constituents (calcination), and form portland cement minerals (clinkerization). The kiln type used in the US is the large capacity rotary kiln. In these kilns a tube with a diameter up to 8 meters is installed at a 3–4 degree angle that rotates 1–3 times per minute. The ground raw material, fed into the

[1] Originally, the wet process was the preferred process, as it was easier to grind and control the size distribution of the particles in a slurry form. The need for the wet process was reduced by development of improved grinding processes.

top of the kiln, moves down the tube toward the flame. In the sintering (or clinkering) zone, the combustion gas reaches a temperature of 1800–2000°C.

In a wet rotary kiln, the raw meal typically contains approximately 36% moisture. These kilns were developed as an upgrade of the original long dry kiln to improve the fineness control in the raw meal. The water is first evaporated in the kiln in the low temperature zone. The evaporation step makes a long kiln necessary. The length to diameter ratio may be up to 38, with lengths up to 230 meters. The capacity of large units may be up to 3600 tonnes of clinker per day. Fuel use in a wet kiln can vary between 5.3 and 7.1 GJ/t clinker [7,8]. The variation is due to the energy requirement for the evaporation, and hence the moisture content of the raw meal. In a dry kiln, feed material with much lower moisture content (0.5%) is used, thereby reducing the need for evaporation and reducing kiln length. The first development of the dry process took place in the US and was a long dry kiln without preheating, or with one stage suspension preheating. Later developments have added multi-stage suspension preheaters (i.e. a cyclone) or shaft preheater. Additionally, pre-calciner technology was more recently developed in which a second combustion chamber has been added to a conventional pre-heater that allows for further reduction of kiln energy requirements. The typical fuel consumption of a dry kiln with 4/5-stage preheating can vary between 3.2 and 3.5 GJ/t clinker [7]. A six-stage preheater kiln can theoretically use as low as 2.9–3.0 GJ/t clinker [8]. The most efficient pre-heater, pre-calciner kilns use approximately 2.9 GJ/t clinker [9–12]. Kiln dust (KD) bypass systems may be required in kilns in order to remove alkalis, sulfates, and chlorides. Such systems lead to additional energy losses since you are removing the sensible heat from the dust.

Once the clinker is formed it is cooled rapidly in order to ensure the maximum yield of alite (tricalcium silicate), an important component for the hardening properties of cement. The main cooling technologies are either the grate cooler or the tube or planetary cooler. In the grate cooler, the clinker is transported over a reciprocating grate passed through by a flow of air. In the tube or planetary cooler, the clinker is cooled in a counter-current air stream. The cooling air is used as combustion air for the kiln.

3.3. Finish grinding

After cooling, the clinker is stored in the clinker dome or silo. The material handling equipment used to transport clinker from the clinker coolers to storage and then to the finish mill is similar to that used to transport raw materials (e.g. belt conveyors, deep bucket conveyors, and bucket elevators) [6]. To produce powdered cement, the nodules of cement clinker are ground. Grinding of cement clinker, together with additives (3–5%) to control the properties of the cement (gypsum and anhydrite) can be done in ball mills, roller mills, or roller presses [13]. Combinations of these milling techniques are often applied. Coarse material is separated in a classifier to be returned for additional grinding.

Electricity use for raw meal and finish grinding depends strongly on the hardness of the material (limestone, clinker, pozzolan extenders) and the desired fineness of the cement as well as the amount of additives. Blast furnace slags are harder to grind and hence use more grinding power, between 50 and 70 kWh/t for a Blaine[2] of 3,500 cm^2/g [7]. Traditionally, ball or tube mills are

[2] Blaine is a measure of the total surface of the particles in a given quantity of cement, or an indicator of the fineness of cement.

used in finish grinding, while many plants use vertical roller mills. In ball and tube mills, the clinker and gypsum are fed into one end of a horizontal cylinder and partially ground cement exits from the other end. Modern ball mills may use between 32 and 37 kWh/t [14,15] for cements with a Blaine of 3,500.

Finished cement is stored in silos, tested and filled into bags, or shipped in bulk on bulk cement trucks or railcars. Additional power is consumed for conveyor belts and packing of cement. The total consumption for these purposes is generally low, and not more than 5% of power consumption.

4. Overview of the US cement industry: production trends and energy use

Portland and Masonry cements are the chief types produced in the United States. More than 90% of the cement produced in the US in 1997 was Portland cement, while Masonry cement accounted for 4.4% of US cement output in 1997 [2].

There were 119 operating cement plants in the US in 1997, spread across 37 states and in Puerto Rico, owned by 42 companies. Portland cement was produced at 118 plants in 1997, while clinker was produced at 108 plants in the US in 1997. Clinker kiln capacity varies between 75 and 1550 kilotonnes per year [16]. Production rates per plant vary between 0.5 and 3.1 million metric tons (Mt) per year. Total production of US cement plants in 1997 was slightly over 82.5 Mt (Fig. 1) [2].

Clinker production, cement production, and materials consumption trends are quite similar. All three categories experienced gradual growth between 1970 and 1997, with prominent dips in the late 1970s and early 1980s. Clinker production increased from 67 Mt in 1970 to 74 Mt in 1997, at an average rate of 0.4% per year, hitting a low of 55 Mt in 1982, and its current high in 1997. Within this slow production increase, the composition of clinker production changed significantly between 1970 and 1997. Clinker produced with the wet process decreased at an average of −2.7% per year, falling from a 60% share of total clinker production in 1970 to a 26% share in 1997. Clinker produced with the dry process increased at an average of 2.6% per year, increasing from a 40% share of total clinker production in 1970 to a 72% share in 1997. Cement production increased at 0.7% per year between 1970 and 1997, rising from 69 Mt in 1970 to 84 Mt in 1997. Portland cement remained the dominant cement type during that time span, maintaining a share between 94% and 96%. Materials consumption increased at an average of 0.5% per year between 1970 and 1997, rising from 115 Mt in 1970 to 133 Mt in 1997 (Fig. 2).

Cement production (0.7% average per year) grew more rapidly than clinker production (0.4% average per year) between 1970 and 1997, which may be due to the increased use of additives and changes in clinker imports. Between 1970 and 1997, the clinker to cement ratio (expressed as clinker production divided by cement production) decreased from 0.97 to 0.88 tonne cement/tonne clinker. The number of clinker plants has decreased from 169 in 1970 to 110 in 1997, while the number of cement plants has fallen from 181 in 1970 to 118 in 1997.

It is defined in terms of square centimeters per gram. The higher the Blaine, the more energy required to grind the clinker and additives to the desired fineness [17].

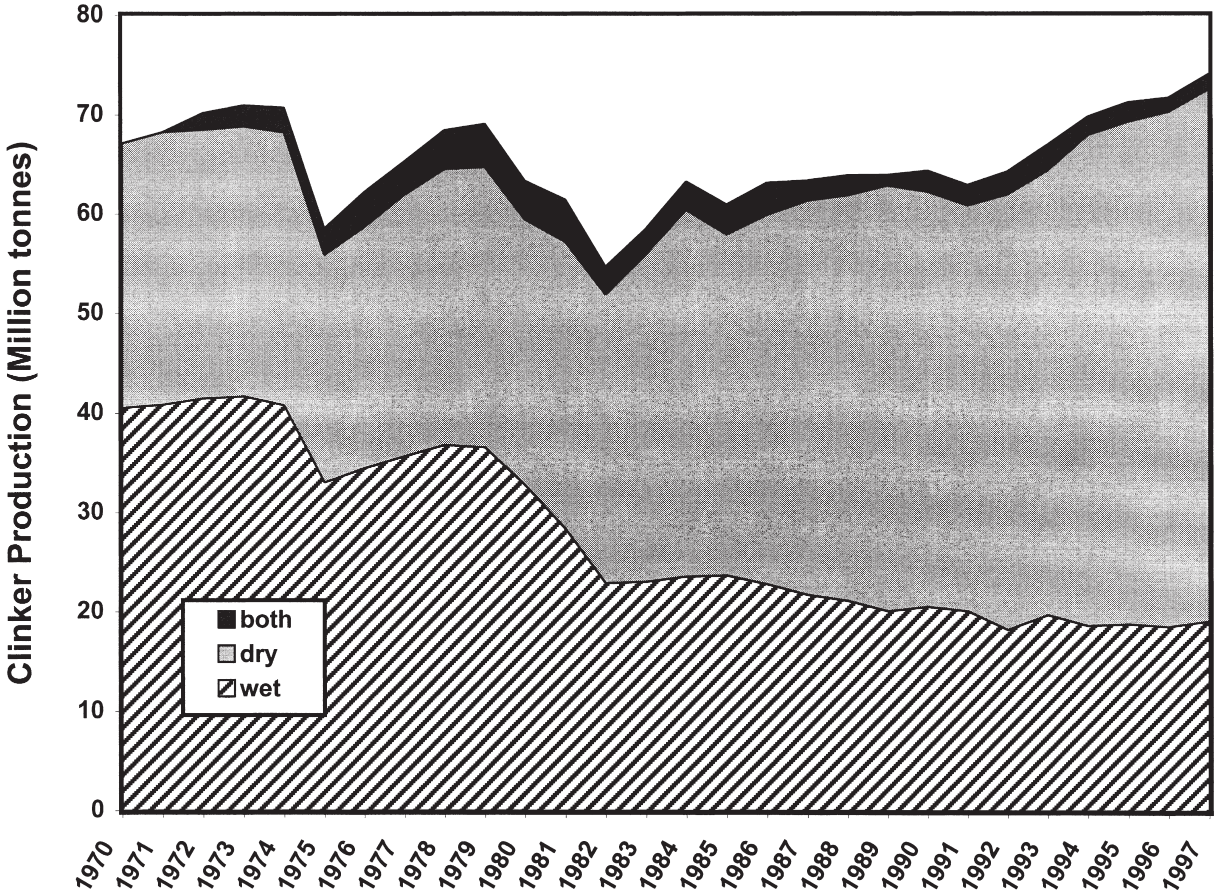

Fig. 1. US clinker production by process, 1970 to 1997 (expressed in million metric tons/year).

4.1. Historical energy use and carbon dioxide emissions trends

Energy consumption in the US cement industry declined between 1970 and 1997. Primary energy intensity decreased at an average of −0.6% per year, from 550 PJ in 1970 to 470 PJ in 1997, although production increased over that time span. The overall energy consumption trend in the US cement industry between 1970 and 1997 shows a gradual decline, though energy consumption started to increase in the early 1990s and increased between 1992 and 1997 at an average of 4% per year. The share of the two main clinker-making processes in energy consumption changed significantly between 1970 and 1997. While the wet process consumed 62% of total cement energy consumption in 1970, it used only 31% in 1997, while energy consumption of the dry process increased from 38% of total cement energy consumption in 1970 to 67% in 1997 (see Fig. 3).

Carbon dioxide emissions from fuel consumption in the cement industry decreased from 11.0 MtC in 1970 to 10.2 MtC in 1997, falling at an average rate of −0.3% per year. Carbon dioxide emissions from clinker calcination increased from 9.3 MtC in 1970 to 10.2 MtC in 1997, at an

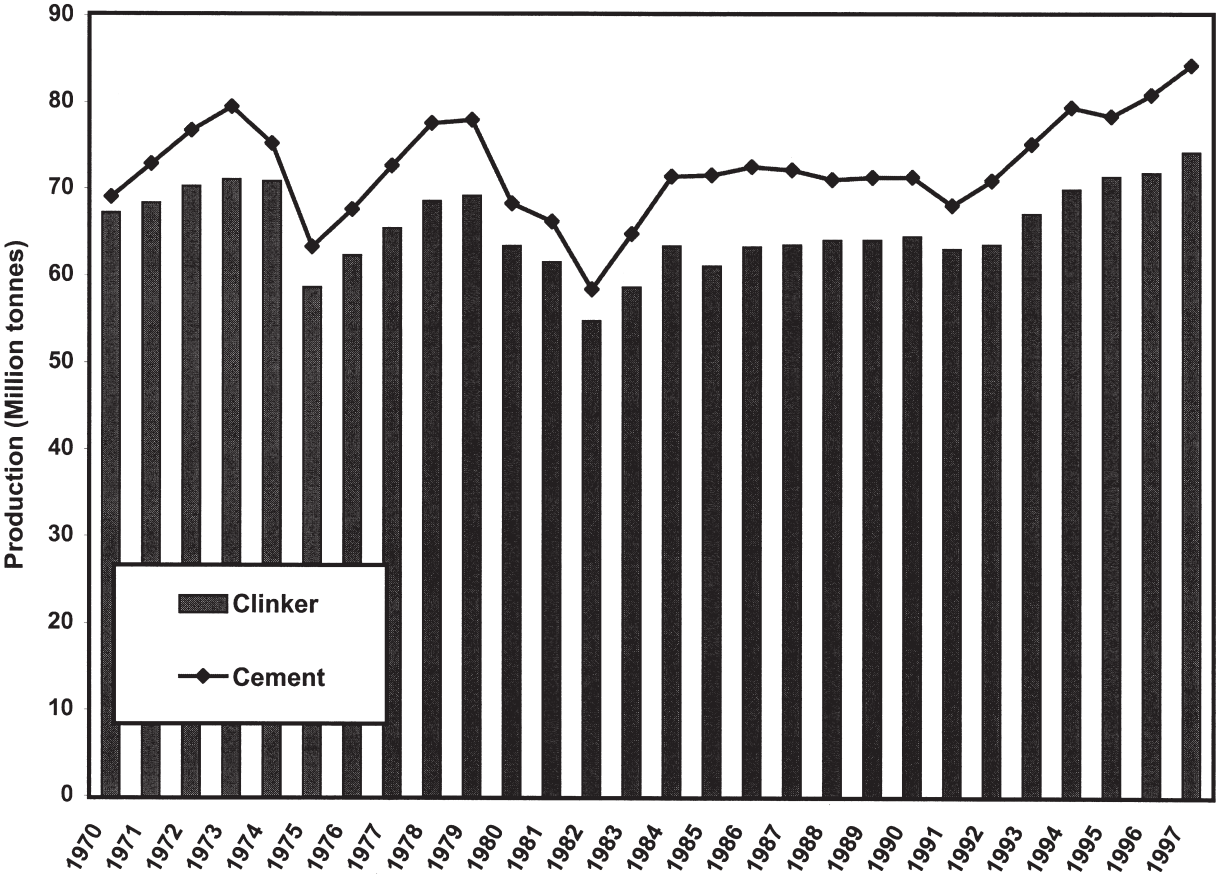

Fig. 2. US cement and clinker production, 1970 to 1997 (expressed in million metric tons/year).

average rate of 0.4% per year, resulting in total carbon dioxide emission increase of 0.03% per year, on average (see Fig. 4). Carbon dioxide emissions from fuel consumption have decreased with energy consumption, and shifting fuel use patterns have affected carbon emissions significantly as well. The largest change occurred in natural gas use, which decreased from a 44% fuel share in 1970 to a 6% fuel share in 1997, due to natural gas price increases and fuel diversification policies after the oil price shocks. Natural gas was commonly substituted by coal and coke, which increased fuel share from 36% in 1970 to 71% in 1997. Oil's share fell from 13% in 1970 to 1% in 1997. Electricity's share increased from 7% in 1970 to 11% in 1997, while the remainder of 1997's fuel share is composed of liquid waste fuel (8%) and tires and solid waste (a combined 2%).

4.2. Historical energy intensity and specific carbon dioxide emission trends

Primary energy intensity in the US cement industry decreased between 1970 and 1997. Primary energy intensity of cement production decreased at an average rate of −1.3% per year, from 7.9 GJ/t in 1970 to 5.6 GJ/t in 1997. While intensity slowly decreased overall between 1970 and

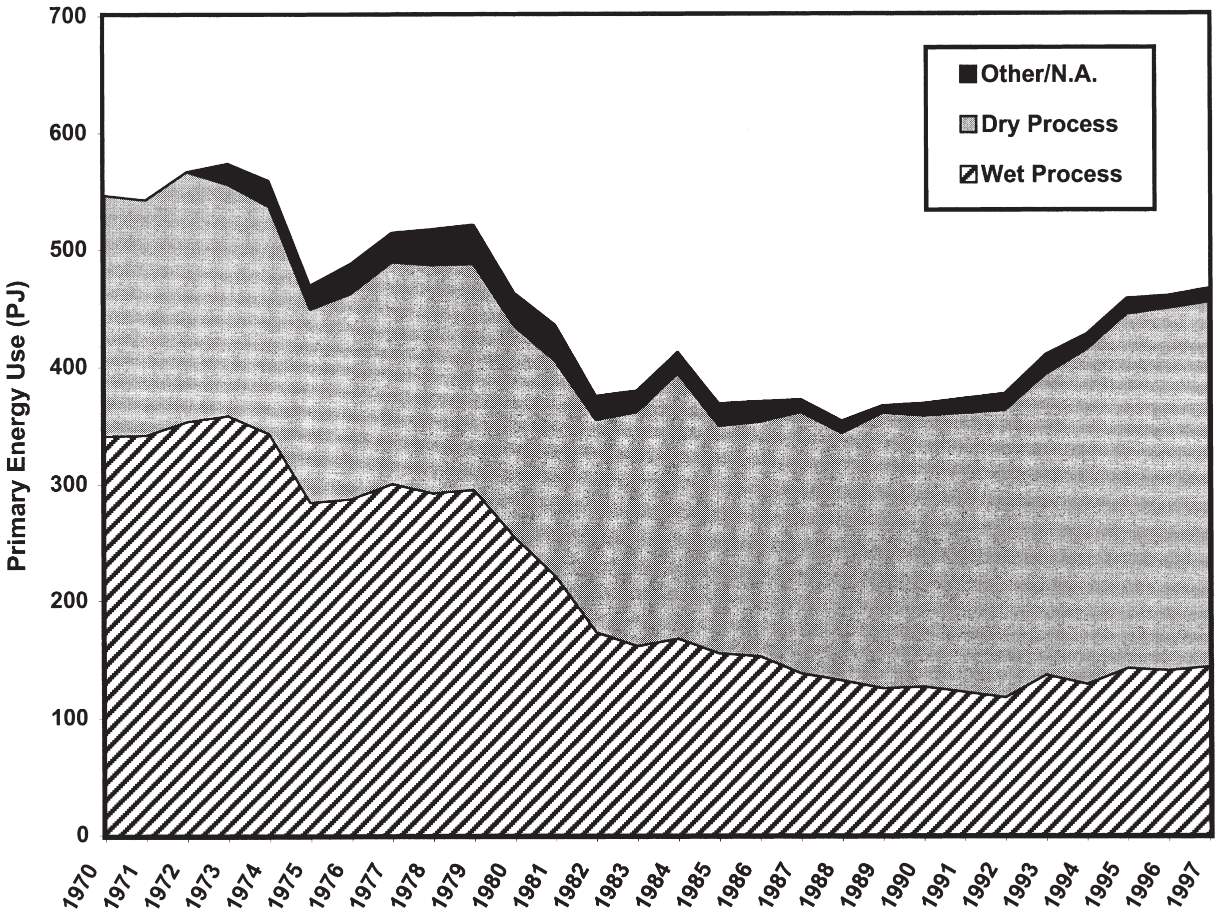

Fig. 3. Primary energy consumption in US cement production by process, 1970 to 1997 (expressed in PJ).

1997, intensity started to climb in the early 1990s, rising 0.9% per year, on average, between 1992 and 1997. Both the wet and dry processes decreased in energy intensity. The energy intensity of the wet process decreased at an average of 0.4% per year between 1970 and 1997 while the energy intensity of the dry process decreased by more than double of that of the wet process, i.e. average of −1.0% per year. Energy intensity of cement production decreased due to increased capacity of the more energy efficient dry process for clinkermaking (see Fig. 1), energy efficiency improvements (see Fig. 5) and reduced clinker production per ton of cement produced (see Fig. 2).

Specific carbon dioxide emission from fuel consumption declined from 160 kg C per tonne of cement in 1970 to 120 kg C/t cement in 1997, decreasing at an average of 1.0% per year. Total carbon dioxide emissions (including emissions from limestone calcination for clinkermaking) decreased at 0.7% per year, on average, from 290 kg C/t cement in 1970 to 240 kg C/t cement in 1997. Like the energy intensity trend, specific carbon dioxide emissions decreased overall between 1970 and 1997, then grew between 1990 and 1997. The specific carbon dioxide emissions from both the wet and dry processes decreased between 1970 and 1997, the wet process at an average of 0.05% per year and the dry process at an average rate of 0.8% per year. The increased

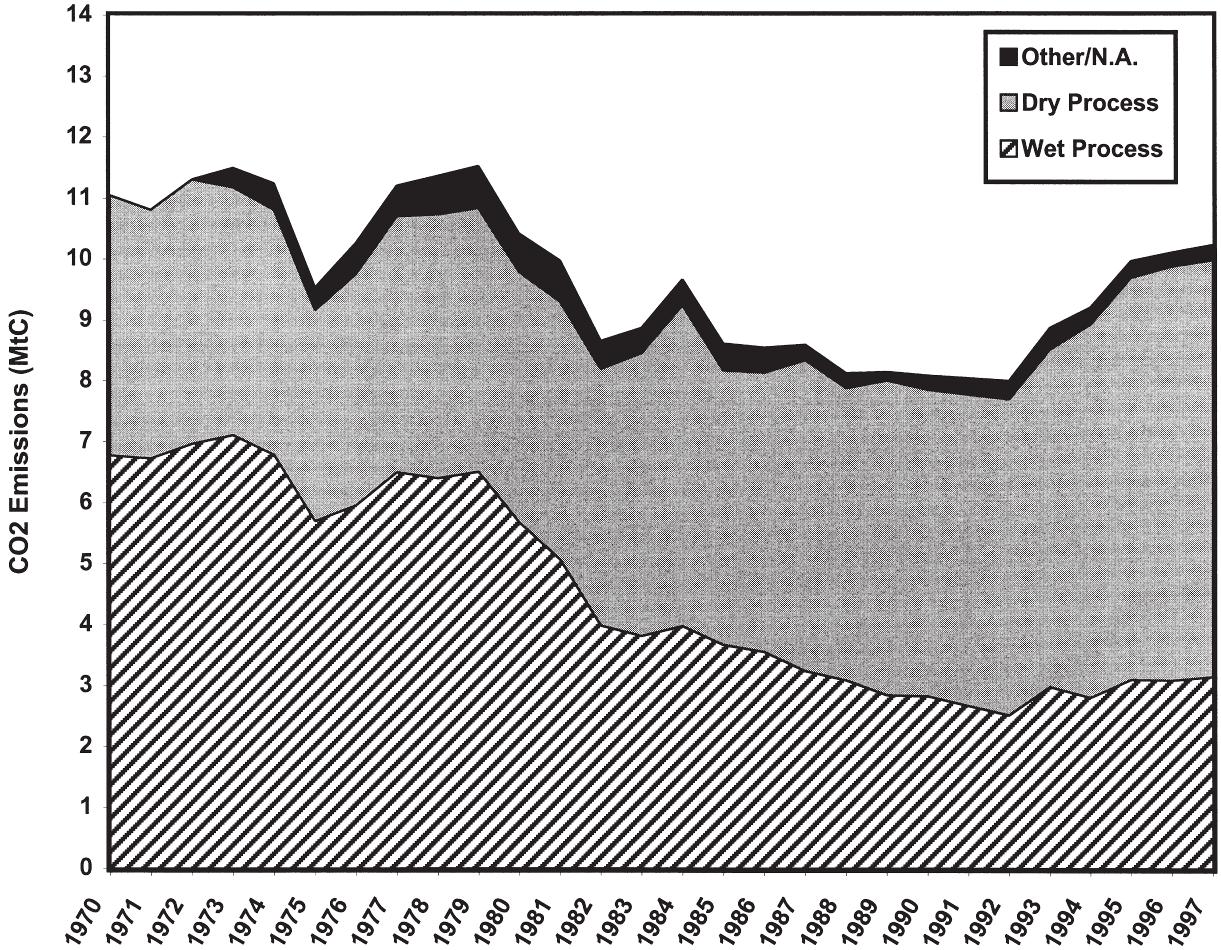

Fig. 4. Carbon emissions from the US cement industry by clinker production process, 1970 to 1997 (expressed in MtC/year).

dry process clinker production capacity, improved energy efficiency, and decreasing clinker/cement-production ratio reduced the specific carbon dioxide emissions, while the substantial fuel shifts towards more carbon intensive fuels like coal and coke contributed to an increase in specific carbon dioxide emissions. Overall, fuel mix trends were more than offset by energy intensity reductions, leading to an overall decrease in specific carbon dioxide emissions.

5. Baseline energy use and carbon dioxide emissions

In 1994, the US cement industry consumed 366 PJ of final energy (about 2% of total US manufacturing energy use) and emitted 19 MtC of carbon dioxide (about 4% of total US manufacturing carbon emissions). Table 1 provides our estimate of 1994 US baseline energy consumption by process.

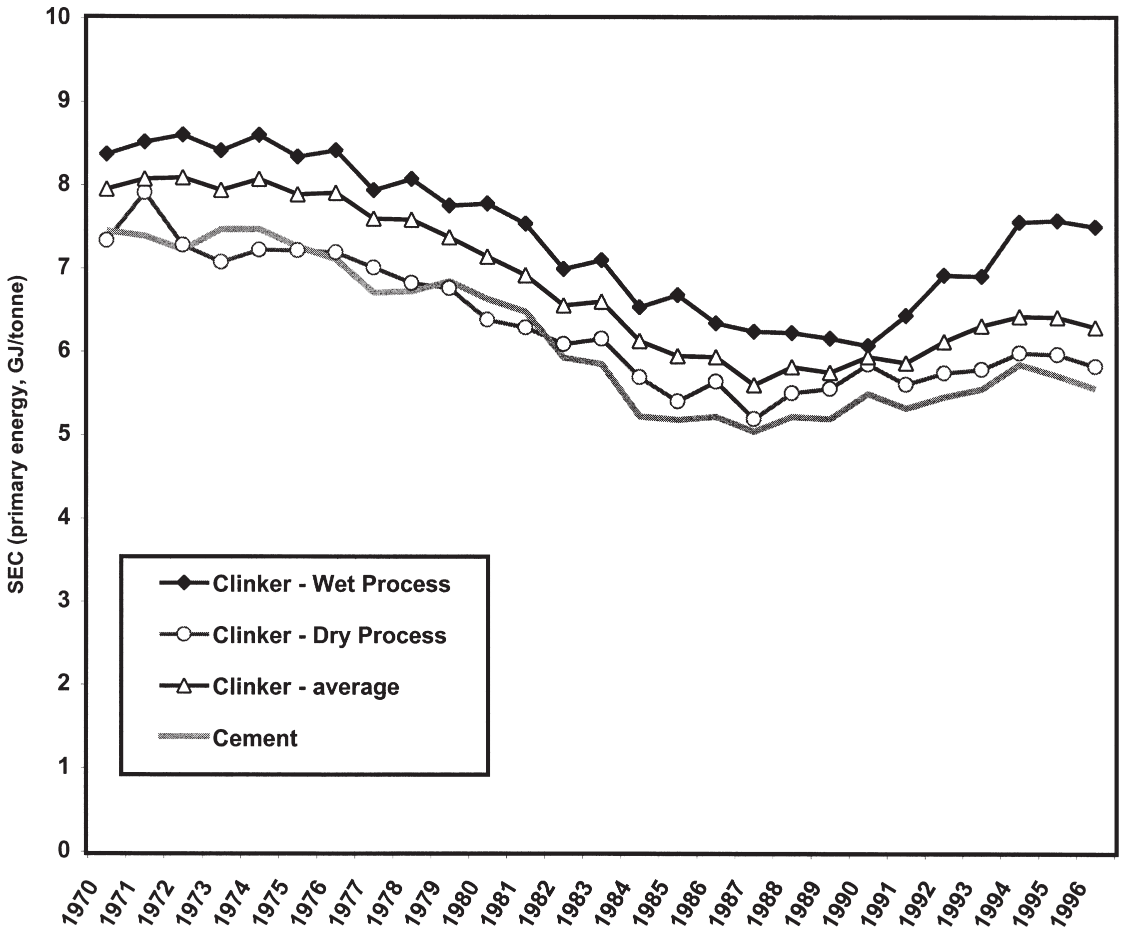

Fig. 5. Primary energy intensity of US cement and clinker production, 1970 to 1997 (expressed in GJ/tonne).

Carbon emissions in the cement industry are produced both through the combustion of fossil fuels and waste fuels, and the calcination of limestone. In the calcination process we assume that 0.14 tonnes of carbon are emitted for every tonne of clinker produced [4]. This amounts to 9.5 MtC given a production of 68.5 million tonnes of clinker in 1994 [18]. We rely on the US Energy Information Administration [3] for 1994 carbon coefficients for the various commercial fuels, except we use the Intergovernmental Panel on Climate Change [4] for coke and breeze. For electricity we use the 1994 average fuel mix for electricity generation in the US. The total 1994 carbon dioxide emission is estimated at 18.9 MtC, of which 9.5 MtC are due to the calcination process.

6. Energy efficiency technologies and measures for the US cement industry

Several technologies and measures exist that can reduce the energy intensity (i.e. the electricity or fuel consumption per unit of output) of the various process stages of cement production. This

Table 1
1994 Energy consumption and specific energy consumption in the US cement industry broken down by process

Process stage	Fuel (PJ)	Electricity (PJ)	Primary energy (PJ)	Fuel SEC (GJ/t)	Electricity SEC (kWh/t)	Primary SEC (GJ/t)	Carbon dioxide emissions energy use (MtC)	Carbon dioxide emissions calcination (MtC)	Carbon dioxide intensity (kgC/t)
Wet process									
Kiln feed preparation[a]	0	4	11	0.0	29	0.3	0.2	0.0	4.6
Clinker production[b]	117	2	124	6.0	30	6.3	2.9	2.7	284.2
Finish grinding[c]	0	4	13	0.0	57	0.6	0.2	0.0	9.1
Total wet process	*117*	*10*	*148*	*5.5*	*133*	*7.0*	*3.2*	*2.7*	279.0
Dry process									
Kiln feed preparation[a]	0	11	33	0.0	34	0.4	0.5	0.0	5.4
Clinker production[b]	211	6	230	4.3	35	4.7	5.3	6.8	245.8
Finish grinding[c]	0	11	34	0.0	57	0.6	0.5	0.0	9.1
Total dry process	*211*	*28*	*296*	*4.0*	*145*	*5.6*	*6.2*	*6.8*	244.6
Total all cement	**328**	**38**	**444**	**4.4**	**142**	**6.0**	**9.5**	**9.5**	**254.4**

[a] Raw materials: In 1994, 123 Mt of raw materials were used in the cement industry [18]. We assume that 29% of raw materials were for the wet process kilns and 71% of raw materials were used for dry process kilns. Additionally we assume an electricity use of 29 kWh/t raw material preparation for wet kilns and 34 kWh/t for dry kilns due to the additional processing [7,19].

[b] Clinker production: According to [18] wet process clinker production was 18.6 Mt while dry process production was 49.3 Mt. Accounting for production from plants with both wet and dry processes on site, we estimate a total clinker production of 68.5 Mt in that year. We assume an average US wet kiln fuel intensity in 1994 of 6.0 GJ/t clinker and an average dry kiln fuel intensity of 4.3 GJ/t [17–20]. Electricity requirements of 30 kWh/t are assumed for fuel preparation and for operating the kiln, fans, and coolers for wet kilns and 35 kWh/t for dry kilns [7].

[c] Finish grinding: We assume that the amount of throughput for finish grinding is the same as the total amount of cement produced in 1994, 21.2 Mt for wet cement and 53.1 Mt for dry cement [18]. We estimate average energy requirements for finish grinding to be 57 kWh/t (52 kWh/short ton) [7].

section provides more detailed estimates on the technologies and measures, their costs, and potential for implementation in the US. Table 2 lists the technologies and measures that we consider in our analysis. Below we will describe selected technologies. A complete technical description of all measures is outside the scope of this paper. For the full description of all measures we refer to [21], which gives a description all technical details and assumptions made to estimate the average potential energy savings and costs of each measure.

6.1. Use of roller mills for raw meal grinding

Traditional ball mills used for grinding certain raw materials (mainly hard limestone) can be replaced by high-efficiency roller mills, by ball mills combined with high pressure roller presses, or by horizontal roller mills. The use of these advanced mills saves energy without compromising product quality. In our measure we estimate an energy savings of 7 kWh/t raw materials [15] through the installation of a vertical or horizontal roller mill. An additional advantage of these

Table 2
Energy-efficient practices and technologies in cement production

Raw materials preparation	
Efficient transport systems	
Raw meal blending systems (dry process)	
Conversion to closed circuit wash mill	
High-efficiency roller mills (dry cement)	
High-efficiency classifiers (dry cement)	
Clinker production (wet)	**Clinker production (dry)**
Kiln combustion system improvements	Kiln combustion system improvements
Kiln shell heat loss reduction	Kiln shell heat loss reduction
Use of waste fuels	Use of waste fuels
Conversion to modern grate cooler	Conversion to modern grate cooler
Optimize grate coolers	Heat recovery for power generation
Conversion to pre-heater, pre-calciner kilns	Low pressure drop cyclones for suspension pre-heaters
Conversion to semi-wet kilns	Long dry kiln conversion to multi-stage pre-heater kiln
	Optimize grate coolers
	Long dry kiln conversion to multi-stage pre-heater, pre-calciner kiln
	Addition of pre-calciner to pre-heater kiln
Finish grinding (applies to both wet and dry cement production)	
Improved grinding media (ball mills)	
High-pressure roller press	
High efficiency classifiers	
Improve mill internals	
General measures	
Preventative maintenance (insulation, compressed air losses, maintenance)	
Reduced kiln dust wasting	
Energy management and process control	
High efficiency motors	
Efficient fans with variable speed drives	
Product changes	
Blended cements	
Reducing the concentration of C_3S in cements	
Reducing fineness of cement for selected uses	

mills is that they can combine raw material drying with the roller process by using large quantities of low grade waste heat from the kilns or clinker coolers [22]. Holderbank [17] claims that 17.6% of installed power was for roller mills for raw grinding, most likely in dry plants, which suggests about 20% of raw grinding capacity is using roller mills. We therefore apply this measure to 72% of raw material preparation in dry process plants. We use an average cost of $5.3/t raw material production [7].

6.2. Kiln combustion system improvements in clinker kilns

Fuel combustion systems in kilns can be contributors to kiln inefficiencies with such problems as poorly adjusted firing, incomplete fuel burn-out with high CO formation, and combustion with excess air [22]. One technique developed in the UK of flame control resulted in fuel savings of 2–10% depending on the kiln type [22]. A recent technology that has been demonstrated in several locations is the Gyro-therm technology that improves gas flame quality while also reducing NO_x emissions. A demonstration project at an Adelaide Brighton plant in Australia found average fuel savings between 5 and 10% as well as an increase in output of 10% [23]. A second demonstration project at the Ash Grove plant in the US (Durkee, OR) found fuel savings between 2.7% and 5.7% with increases in output between 5 and 9% [23,24]. We assume a fuel saving of 4%, and currently apply this measure on a percentage basis to all kilns using gas as their primary or secondary fuel, or about 6% of clinker production capacity. Costs for the technology vary by installation. We assume an average cost of \$0.98/t clinker capacity based on reported costs in the demonstration projects.

6.3. Process control and management systems

Heat from the kiln may be lost through non-optimal process conditions or process management. Automated computer control systems may help to optimize the combustion process and conditions. Improved process control will also help to improve the product quality, e.g. reactivity and hardness of the produced clinker, which may lead to more efficient clinker grinding. In cement plants across the world, different systems are used, marketed by different manufacturers. Most modern systems use so-called “fuzzy logic” or expert control, while some use rule-based control strategies. Expert control systems do not use a modeled process to control process conditions, but try to simulate the best controller, using information from various stages in the process. These systems are also described as “neural networks”. One such system, called LINKman, was originally developed in the United Kingdom by Blue Circle Industries and SIRA [25]. The first system was installed at Blue Circle’s Hope Works in 1985, which resulted in a fuel consumption reduction of nearly 8% [25]. The LINKman system has successfully been used in both wet and dry kilns. After their first application in 1985, modern control systems now find wider application and can be found in many European plants. Additional process control systems include the use of on-line analyzers that permit operators to instantaneously determine the chemical composition of raw materials being processed in the plant, thereby allowing for immediate changes in the blend of raw materials. A uniform feed allows for more steady kiln operation, thereby saving ultimately on fuel requirements. Energy savings from such process control systems may vary between 2.5% and 10% [25–27], and the typical savings are estimated at 2.5–5%. We assume the savings of 4% of fuel intensity (0.2 GJ/t clinker) and power savings of 3% of electricity intensity or 4 kWh/t cement [17,26]. The economics of advanced process control systems are very good and payback periods can be as short as 3 months [25]. The system at Blue Circle’s Hope Works needed an investment of £203,000 (1987), equivalent to £0.2/t clinker (\$0.3/t clinker) [25], including measuring instruments, computer hardware and training. Holderbank [17] notes an installation cost for on-line analyzers of \$0.8–1.7/t clinker. We therefore use an installation cost of \$1.5/t clinker capacity. We assume that this system can still be applied to kilns older than 20 years or 49% of industry kiln capacity.

6.4. Wet process conversion to multi-stage pre-heater, pre-calciner kiln

In some cases, it may be feasible to convert a wet process facility to a state-of-the art dry process production facility that includes both pre-heater and pre-calciner technology. Average fuel consumption in US wet kilns is estimated at 6.0 GJ/t. Studies of several kiln conversions in the US in the 1980s found fuel savings of 3.4 GJ/t, but baseline wet kiln energy use was higher than current levels (6.8 GJ/t) [22]. In Hranice, in the Czech Republic, a 1050 tonnes per day wet process plant was converted to a dry kiln plant with a new kiln energy consumption of 3.13 GJ/t clinker [28]. This equals a saving of 2.9 GJ/t from the US average fuel intensity for wet kilns. We assume fuel savings of 2.8 GJ/t and an increase in power use of about 10 kWh/t clinker [8] The cost of converting a wet plant to a dry process plant may be high, as it involves the full reconstruction of an existing facility. Costs may vary between \$50/t clinker capacity and \$110/t clinker capacity [29,30]. We assume a cost of \$75/t clinker capacity. We apply this measure to all wet kilns over 30 years of age, or 42% of wet kiln capacity.

6.5. Energy efficient finish grinding

The energy efficiency of ball mills for use in finish grinding is relatively low, consuming up to 33–45 kWh/t cement, depending on the fineness of the cement [15,31]. Several new mill concepts exist that can significantly reduce power consumption in the finish mill to 22–33 kWh/t cement, including roller presses, roller mills, and roller presses used for pre-grinding in combination with ball mills [13–15]. Roller mills employ a mix of compression and shearing, using 2–4 grinding rollers carried on hinged arms riding on a horizontal grinding table [13,15]. In a high-pressure rolling mill, two rollers put the material under a pressure of up to 3500 bar [32], improving the grinding efficiency dramatically [14].

Air swept vertical roller mills with integral classifiers are used for finish grinding, whereas a recent off-shoot technology which is not air swept is now being used as a pre-grinding system in combination with a ball mill. A variation of the roller mill is the air swept ring roller mill which has been shown to achieve an electricity consumption of 25 kWh/t with a Blaine of 3000 [33]. A new mill concept is the Horomill, first demonstrated in Italy in 1993 [32]. In the Horomill a horizontal roller, within a cylinder, is driven. The centrifugal forces resulting from the movement of the cylinder cause a uniformly distributed layer to be carried on the inside of the cylinder. The layer passes the roller (with a pressure of 700–1000 bar) [31]. The finished product is collected in a dust filter. The Horomill is a compact mill that can produce a finished product in one step and hence has relatively low capital costs. Grinding portland cement with a Blaine of 3200 cm^2/g consumes approximately 23 kWh/t [32] and even for pozzolanic cement with a Blaine of 4000 power use may be as low as 28 kWh/t [32].

Today, high-pressure roller presses are most often used to expand the capacity of existing grinding mills, and are found especially in countries with high electricity costs or with poor power supply [14]. After the first demonstration of the Horomill in Italy, this concept is now also applied in plants in Mexico [32], Germany, the Czech Republic and Turkey [34]. The electricity savings of a new finish grinding mill when replacing a ball mill is estimated at 27 kWh/t. We further estimate a savings of 8 kWh/t for the addition of a pre-grinding system to a ball mill [15,35,36]. Capital cost estimates for installing a new roller press vary widely in the literature, ranging from low estimates like \$2.5/t cement capacity [17] or \$3.6/t cement capacity [37] to high estimates of \$8/t cement capacity [7]. We estimate the costs at approximately \$4/t cement capacity. The capital costs of roller press systems are lower than those for other systems [37] or at least comparable [38]. Some new mill concepts may lead to a reduction in operation costs of as much as 30–40% [39]. The total grinding capacity in the US in 1994, including white cement and dedicated grinding facilities, was 91.23 Mt [5]. Of this amount, only 8% had already installed roller presses in 1994. We assume that 50% of large ball mills (>100 kt capacity) older than 25 years (22% of US grinding capacity) are retrofitted with advanced mill systems, and 50% of large ball mills between 10 and 25 years old are retrofitted with roller press pre-grinding systems (19% of US grinding capacity).

6.6. Product change — blended cements

The production of blended cements involves the intergrinding of clinker with one or more additives (fly ash, pozzolans, blast furnace slag, silica fume, volcanic ash) in various proportions. The use of blended cements is a particulary attractive efficiency option since the intergrinding of clinker with other additives not only allows for a reduction in the energy used (and carbon emissions) in clinker production, but also corresponds to a reduction in carbon dioxide emissions in calcination as well. Blended cements are very common in Europe, and blast furnace and pozzolanic cements account for about 12% of total cement production with portland composite cement accounting for an additional 44%. In the US, some of the most prevalent blending materials are fly ash and blast furnace slag. A recent analysis of the US situation cited an existing potential of producing 31 Mt of blended cement in 2000 using both fly ash and blast furnace slag, or 36% of US capacity [40]. This analysis was based on estimates of the availability of intergrinding materials and then surveying ready-mix companies to estimate feasible market penetration. The blended cement produced would have, on average, a clinker/cement ratio of 65% or would result in a reduction in clinker production of 9.3 Mt. The reduction in clinker production corresponds to a specific fuel savings of 1.42 GJ/t. We assume an increase in fuel use of 0.09 GJ/t for drying of the blast furnace slags but a corresponding energy saving of 0.2 GJ/t for reducing the need to use energy to bypass kiln exit gases to remove alkali-rich dust. We assume a saving of 5 kcal/kg per percent bypass [13]. The bypass savings are due to the fact that blended cements offer an additional advantage in that the interground materials also lower alkali–silica reactivity (ASR) thereby allowing a reduction in energy consumption needed to remove the high alkali content kiln dusts. This measure therefore results in total fuel savings of 1.41 GJ/t (blended) cement. Electricity consumption, however, is expected to increase due to the added electricity consumption associated with grinding the blending materials. We estimate an increase in electricity consumption of 17 kWh/t [32]. We assume an investment cost of \$0.7/t cement capacity which reflects the cost of new delivery and storage capacity (bin and way-feeder). This measure is applied to 42% of total US clinker production, based on results of the PCA-study.

Table 3 summarizes the assumptions for the potential energy savings and costs for each of the practices and technologies. [21] provides more technical details for each of the measures in Table 3.

Table 3
Energy savings, costs and carbon dioxide emission reductions for energy efficient practices and technologies for cement making in the US in 1994. The energy savings are expressed per tonne of product. Carbon dioxide savings are estimated per tonne of cement[a]

Option	Production (Mtonne)	Fuel savings (GJ/tonne)	Electricity savings (GJ/tonne)	Primary energy savings (GJ/tonne)	Annual operating costs (US$/tonne)	Retrofit capital cost (US$/tonne)	Carbon dioxide emissions reductions (kgC/t cement)	Share of production measure applied (percent)
Raw materials preparation (wet process)								
Mechanical transport systems	34.9	0.0	0.01	0.02	0.00	3.00	0.53	46%
Raw materials preparation (dry process)								
Mechanical transport system	87.6	0.00	0.01	0.02	0.00	3.00	0.53	19%
Raw meal blending system	87.6	0.00	0.01	0.01	0.00	3.70	0.26	20%
High efficiency roller mills	87.6	0.00	0.03	0.08	0.00	5.30	1.85	72%
High efficiency classifiers	87.6	0.00	0.01	0.03	−0.07	2.00	0.71	70%
Clinker production (wet process)								
Kiln combustion systems	19.5	0.20	0.00	0.24	0.00	0.98	10.30	5%
Kiln shell heat loss reduction	19.5	0.15	0.00	0.15	0.00	0.25	6.44	46%
Use of waste fuels	0.60	0.00	0.60	0.00	1.00	25.76	20%	20%
Conversion to grate cooler	19.5	0.30	−0.01	0.30	0.10	0.40	13.74	6%
Conversion to semi-wet process	19.5	1.26	−0.01	1.21	0.14	1.80	53.31	10%
Optimize heat recovery (grate cooler)	19.5	0.10	0.00	0.10	0.00	0.20	4.29	73%
Conversion to precalciner kiln	19.5	2.80	−0.04	2.69	−0.90	75.00	118.67	43%
Clinker production (dry process)								
Kiln combustion systems	49.0	0.20	0.00	0.17	0.00	0.98	8.80	6%
Kiln shell heat loss reduction	49.0	0.20	0.00	0.15	0.00	0.25	7.67	17%
Use of waste fuels	49.0	0.60	0.00	0.60	0.00	1.00	30.70	8%
Conversion to grate cooler	49.0	0.30	−0.01	0.30	0.10	0.50	16.37	6%
Low pressure-drop cyclones	49.0	0.00	0.01	0.04	0.00	3.10	0.74	31%
Heat recovery for power generation	49.0	0.00	0.07	0.22	0.30	1.80	3.68	4%
Conversion to multi-stage preheating	49.0	0.90	0.00	0.90	0.00	20.00	46.05	15%
Conversion to pre-calciner kiln	49.0	0.40	0.00	0.40	−1.10	10.00	20.46	21%
Conversion to PH/PC-kiln	49.0	1.30	0.00	1.30	0.00	28.00	66.51	8%
Optimize heat recovery (grate cooler)	49.0	0.10	0.00	0.10	0.00	0.20	5.12	65%
Finish grinding								
Improved grinding media	74.3	0.00	0.01	0.02	0.00	0.70	0.32	25%
High-pressure roller press	74.3	0.00	0.03	0.09	−0.20	2.50	1.28	19%

(continued on next page)

Table 3 (*continued*)

Option	Production (Mtonne)	Fuel savings (GJ/tonne)	Electricity savings (GJ/tonne)	Primary energy savings (GJ/tonne)	Annual operating costs (US$/tonne)	Retrofit capital cost (US$/tonne)	Carbon dioxide emissions reductions (kgC/t cement)	Share of production measure applied (percent)
Roller press/Horomill	74.3	0.00	0.10	0.30	−1.00	4.00	4.33	22%
High efficiency classifiers	74.3	0.00	0.01	0.03	−0.60	2.50	0.48	40%
General measures								
Variable speed drives	74.3	0.00	0.03	0.10	0.00	0.95	1.68	24%
High-efficiency motors	74.3	0.00	0.02	0.06	0.00	0.20	0.93	50%
Process control systems	74.3	0.18	0.02	0.22	0.00	1.60	9.91	49%
Preventative maintenance	74.3	0.05	0.01	0.08	0.02	0.01	2.94	100%
Product changes								
Blended cement	74.3	1.53	−0.05	1.36	0.00	0.70	76.31	29%
Higher alkali allowance	74.3	Only included in clinker production for blended cement (see blended cement)						
Reduced fineness for selected uses	74.3	Not included in analysis, due to lack of available data on specific uses and markets for cement and concrete						

[a] The energy savings are expressed per tonne of product. To estimate savings per tonne of cement in the US multiply the savings per tonne product with production of the specific product and the share to which the measure is applied. The applied share is an estimate of the potential capacity to which the measure can be applied as share of the production (second column) of the specific product.

7. Energy efficiency and CO_2 emission reduction potential in the cement industry

In this section we assess the cost-effectiveness of the potential for energy efficiency improvement and CO_2 emission reduction. We analyse two different strategies. The first strategy assumes that there will be no changes in product standards, and hence no change in the production structure of 1994 (determined on the basis of raw material needs and product mix). The second strategy assumes that product standards will be changed, to allow the production of blended cement, as is common in most countries outside the US. This is a departure from the 1994 mix of raw materials and products, as less clinker will be needed to produce the same quantity of cement. However, this will reduce the potential energy savings due to practices and technologies in the clinkermaking process.

7.1. Conservation supply curve for cement making (without product change)

We identified cost-effective energy savings of 48 PJ and carbon emissions reductions of 1.0 MtC for cement making in 1994 which represents 11% of the total US cement industry's energy use and 5.4% of the total carbon emissions (including calcination). Fig. 6 ranks the energy efficiency measures in a conservation supply curve; the cost-effective measures are those which fall below the average weighted energy supply cost for 1994, and are therefore cost effective at

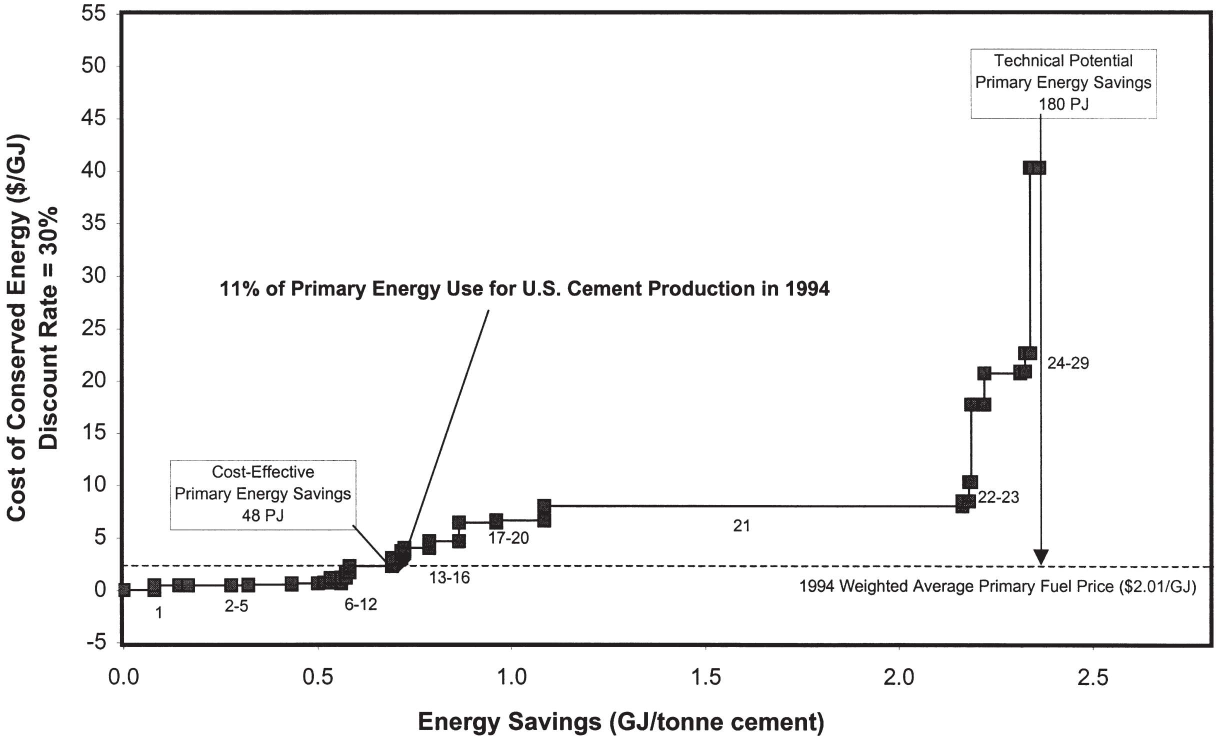

Fig. 6. Energy conservation supply curve for energy efficiency measures in the US cement industry. The measures exclude the production of blended cement. The horizontal axis depicts the cumulative primary energy savings (expressed in GJ/tonne cement). The vertical axis represents the cost of conserved energy (expressed in $/GJ primary energy saved), using a discount rate of 30%. The numbers of the measures and names can be found in Table 4.

1994 energy prices using a discount rate of 30%. Table 4 provides a list of the measures ranked by their cost of conserved energy, internal rate of return, and their simple payback periods.

The analysis shows that there is a large technical potential for energy efficiency improvement (excluding product changes) of 180 PJ, or 40%. However, only a small part is cost-effective at current investment and energy costs. This limits the potential to 11% (or 48 PJ). Due to the carbon dioxide emissions from calcination the overall effect on carbon dioxide emissions is divided by a factor two, when compared to energy efficiency improvement. The analysis shows that retrofit measures for efficiency improvement (e.g. capital-intensive kiln conversions) alone limit the potential for energy efficiency improvement. However, in practice new plants will be built to replace aging facilities, or to supply cement to regions with high growth in cement consumption. In recent years new energy-efficient kilns have been built in the Pacific Northwest, Florida and Utah. Capital stock turnover is hence an important driver for energy efficiency in an industry with capital intensive lay-outs, despite the large contribution of energy costs to total production costs.

7.2. Conservation supply curve for cement making (with product change)

The discussion above assumes that the US cement industry will produce the same product mix as in 1994. However, many countries in the world produce blended cement with a lower clinker

Table 4
Energy efficiency improvement measures in the US cement industry, ranked by CCE. The simple payback period and internal rate of return are also given[a]

	Energy efficiency measure	Primary energy savings (GJ/tonne)	Carbon dioxide emission reduction (ktC)	CCE primary energy ($/GJ-saved)	Internal rate of return (%)	Simple payback period (years)
1	Preventative maintenance	0.08	219	0.04	1254%	0.1
2	Kiln heat loss reduction (w)	0.06	58	0.50	107%	0.9
3	Kiln heat loss reduction (d)	0.02	62	0.50	107%	0.9
4	Use of waste fuels (w)	0.11	101	0.50	107%	0.9
5	Use of waste fuels (d)	0.04	120	0.50	107%	0.9
6	Conversion to semi-wet kiln	0.11	104	0.56	114%	0.9
7	Clinker cooler grate (w)	0.07	62	0.68	6%	1.3
8	Clinker cooler grate (d)	0.06	163	0.68	79%	1.3
9	Conversion to grate cooler (w)	0.02	16	0.76	102%	1.0
10	Conversion to grate cooler (d)	0.02	48	0.76	101%	1.0
11	High efficiency motors	0.03	35	1.17	33%	2.8
12	Kiln combustion system (w)	0.01	11	1.23	44%	2.3
13	Kiln combustion system (d)	0.01	25	1.72	31%	3.2
14	Process control system	0.11	361	2.32	20%	4.3
15	Variable speed drives	0.02	30	3.08	6%	7.3
16	Cogeneration (steam)	0.01	7	3.72	N/A	>25
17	Roller press/Horomill	0.06	69	4.03	7%	10.3
18	Precalciner on preheater kiln	0.08	210	4.69	18%	5.4
19	Conversion to preheater kiln	0.10	261	6.46	8%	12.1
20	Conversion to precalciner kiln	0.12	338	6.67	8%	12.5
21	Wet to precalciner kiln conversion	1.08	1009	8.03	7%	13.0
22	Pre-grinding-HP roller mill	0.02	19	8.51	N/A	21.7
23	Improved grinding media	0.01	6	10.35	N/A	24.6
24	High efficiency classifiers (d)	0.03	44	17.77	N/A	18.8
25	High efficiency roller mill	0.09	117	20.74	N/A	>25
26	Low pressured drop cyclones	0.01	11	20.94	N/A	>25
27	High efficiency classifiers (w)	0.01	14	22.69	N/A	>25
28	Mechanical transport systems (d)	0.01	9	40.32	N/A	>25
29	Mechanical transport systems (w)	0.02	9	40.32	N/A	>25

[a] (d): applies to dry process kilns; (w): applies to wet process kilns.

content which can reduce the energy intensity of cement considerably. Producing blended cements may have synergetic effects, as it can help to replace the most energy intensive kilns in a given region (depending on various conditions, e.g. transport distances of resources, limestone reserves). In this section we assess the role of clinker replacement by cementious additives. We assume that the use of additives will reduce the total amount of clinker produced, maintaining the cement production level of 1994. Hence, energy efficiency measures in clinker making will provide lower total energy savings. The results are presented in Fig. 7.

The switch to the production of blended cement, replacing 15% of 1994 clinker production, does not affect the technical potential for energy efficiency improvement much. However, the cost-effective potential increases from 11% to 18%. The effects on carbon dioxide emissions are more profound, due to the reduced clinker production, which in turn reduces emissions from energy use and limestone calcination. The total technical potential for carbon dioxide emissions is almost 5.3 MtC (or 28%) and the cost-effective potential is estimated at 3.1 MtC (or 16%).

We have assumed that both dry and wet process cement plants are taken out of production in equal shares. In practice, the introduction of blended cement may curb the production of the less efficient kilns, and may impact energy use more. Ready-mix producers are among the largest users of cement in the US. Ready-mix producers already use fly-ash in the production of concrete.

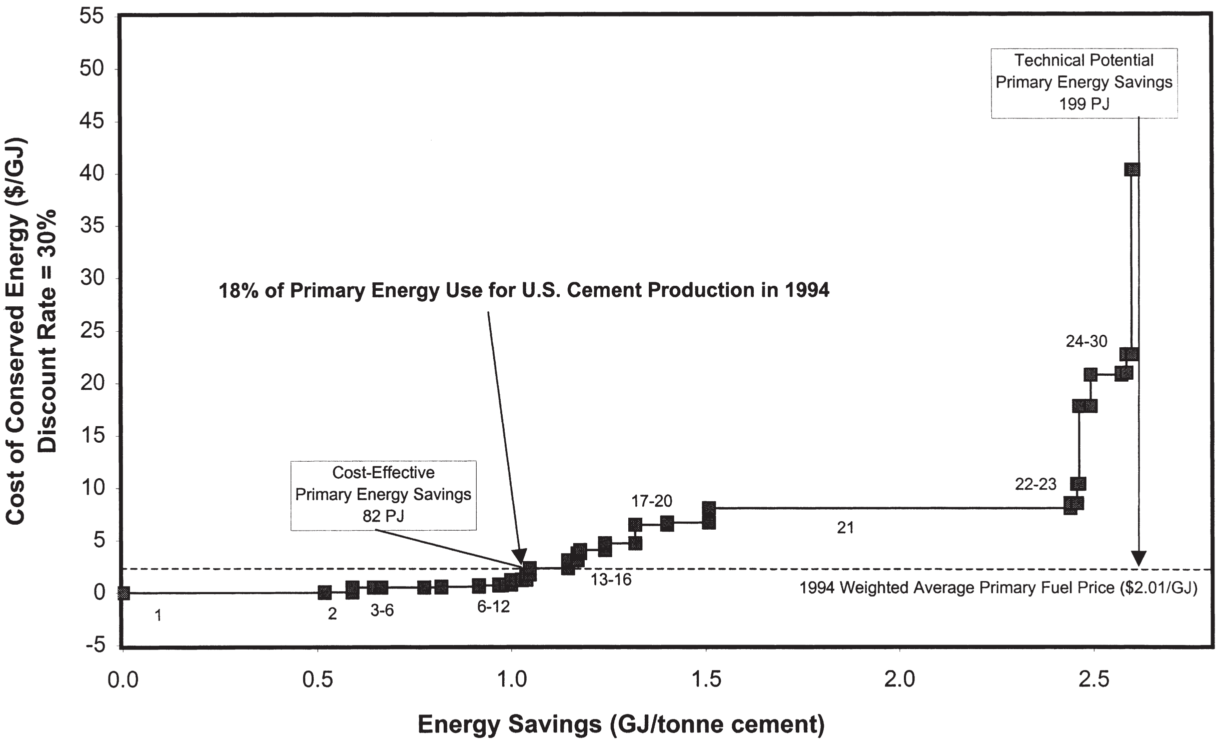

Fig. 7. Energy conservation supply curve for energy efficiency measures in the US cement industry, including the production of blended cement (measure 1). The horizontal axis depicts the cumulative primary energy savings (expressed in GJ/tonne cement). The vertical axis represents the cost of conserved energy (expressed in $/GJ primary energy saved), using a discount rate of 30%.

However, no statistical information is available on the actual use in concrete making. Although ready-mix producers use additives, the intergrinding of additives at the cement plant may have additional benefits over use at the ready-mix producer (see above). The use of additives at the cement plant may not affect the concrete production process, but additional research is needed to assess the potential impact and net impact on energy intensity for concrete-making.

Table 5 summarises the results of the technical and economic analysis of the potentials for energy efficiency improvement in the US cement industry, based on the 1994 reference situation. Although some changes have taken place in the technologies used in the US cement industry, e.g. a new clinker plant has started production at Devil's Slide (UT) and other plants have been rebuilt, there have been no dramatic changes in the industry. Still, the potential impact of some of the measures may be different today compared to 1994. We used 1994, because that was the latest year for which energy data was available at a suitable aggregation level from the Department of Energy's Energy Information Administration. A regular update of this study may be needed to account for the dynamics of the industry in the assessment of energy efficiency potentials, as well as development in cement-making technology.

8. Conclusions

We have analyzed historic trends for energy efficiency in the US cement industry, as well as identified cost-effective energy and carbon dioxide savings that can be achieved in the near future. We discussed this industry at the aggregate level (SIC 324), which includes establishments engaged in manufacturing hydraulic cements, including portland, natural, masonry, and pozzolana when reviewing industry trends and when making international comparisons. We also focused on the aggregate level for a detailed analysis of energy use and carbon dioxide emissions by process, specific energy efficiency technologies and measures to reduce energy use and carbon dioxide emissions, and the energy efficiency and carbon dioxide emissions reduction potential for cement production in the US.

We found that coal and coke are currently the primary fuels for the sector, supplanting the dominance of natural gas in the 1970s. Between 1970 and 1997, primary physical energy intensity for cement production dropped 30%, from 7.9 GJ/t to 5.6 GJ/t, while carbon dioxide intensity from fuel consumption (carbon dioxide emissions expressed in tonnes of carbon per tonne cement)

Table 5
Summary of the technical and cost-effective potential for energy efficiency improvement in the US cement industry, and impact on carbon dioxide emissions, for the reference year 1994. Carbon dioxide emission reduction is expressed as share of the total emissions (including emissions from calcination in the clinker making)

	Energy efficiency improvement		Carbon dioxide emissions	
	Technical potential (PJ)	Cost-effective potential (PJ)	Technical potential (MtC)	Cost-effective potential (MtC)
Current product mix	180 (40%)	48 (11%)	3.5 (18%)	1.0 (5%)
Blended cement	199 (45%)	82 (18%)	5.3 (28%)	3.1 (16%)

dropped 25%, from 0.16 tC/t to 0.12 tC/t. Total carbon dioxide intensity due to fuel consumption and clinker calcination dropped 17%, from 0.29 tC/t to 0.24 tC/t.

We examined 30 energy-efficient technologies and measures and estimated energy savings, carbon dioxide savings, investment costs, and operation and maintenance costs for each of the measures. We constructed an energy conservation supply curve for the US cement industry which found a total cost-effective reduction of 0.6 GJ/tonne of cement, consisting of measures having a simple payback period of 3 years or less. This is equivalent to potential energy savings of 11% of 1994 energy use for cement making and a saving of 5% of total 1994 carbon dioxide emissions by the US cement industry.

Assuming the increased production of blended cement in the US, as is common in many parts of the world, the technical potential for energy efficiency improvement would not change considerably. However, the cost-effective potential would increase to 1.1 GJ/t cement or 18% of total energy use, and carbon dioxide emissions would be reduced by 16% due to the reduced clinker production. This demonstrates that use of blended cement is a key cost-effective strategy for energy efficiency improvement and carbon dioxide emission reductions in the US cement industry.

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